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REDUCTION OF THE UNCERTAINTY OF RADAR RANGE CORRECTION

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Scientific Report Number 2

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AIR FORCE GEOPHYSICS LABORATORY
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A correction for the range error induced by the ionosphere is examined for a representative 425 Mhz radar. A technique has been developed to update the basic prediction of the median so that the residual day-to-day variability of the range correction is reduced. This technique is examined over a descending phase of a solar cycle using measurements of total electron content from Hamilton, Massachusetts.

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The results show that hourly updating can reduce the residual error in range correction by 60 percent, and three-hourly updating will provide a 30 percent reduction in day-time when the absolute error in range correction is greatest. During periods of rapid changes in TEC such as, sunrise and sunset, and periods of sever magnetic disturbance updating in 15-30 minute intervals is recommended to significantly reduce error.

PREFACE

The author would like to thank Mr. J. Klobuchar of the Air Force Geophysics Laboratory for use of the TEC data from Hamilton, Mass., Dr. C. Rush of the Air Force Geophysics Laboratory for helpful discussions of prior work and Mr. R. S. Allen of the Air Force Geophysics Laboratory for many useful comments and suggestions. This work was performed under Air Force Contract F19628-76-C-0255.

INTRODUCTION

Precision tracking radars encounter an error in range measurement which is directly proportional to the total electron content (TEC) of the ionosphere along the ray path to the target. A median correction for this error can be derived from models which predict the monthly median variation of TEC and other ionospheric parameters, but there is a residual error that reflects the difference between the monthly median and the actual daily values. It is this error that must be reduced to improve the accuracy of radar systems.

In deriving a technique to reduce this error, it was assumed that this day-to-day variability represents features that change only gradually in a period of a few hours (DuLong and Allen[1], 1976; Allen[2] et al., 1976). If this assumption is valid, the use of local measurements of a particular parameter and the prediction of its median could be combined in a technique for adaptive modelling that would provide a significant reduction in the residual error.

The parameter used here to examine the technique is TEC, obtained from the Hamilton, Mass. measurements of the Faraday rotation of the VHF beacon on the ATS-3 geostationary satellite, and reduced to equivalent vertical electron content at the subionospheric point 38.7° N, 70.7° W geographic, assuming the height of the centroid of the ionosphere to be near 420 km. (Titheridge[3], 1972; Klobuchar[4] et al., 1973). These data were recorded continuously from 1968 through 1976. Since this period spanned the descending phase of the recent solar cycle it was possible to evaluate solar cycle variations as well as seasonal and diurnal changes.

DAY-TO-DAY VARIABILITY

Isopleths of the monthly mean of the observed TEC in units of 10^{15} el/m^2, in Figure 1, summarize the diurnal, seasonal, and solar cycle behavior of this archive data. The 12-month running mean sunspot numbers ($\bar{R}_Z$) vary from 110 at solar maximum to 10 at solar minimum. This is representative of median solar conditions as determined by observations of sunspot number over the last 20 solar cycles. During this period the 12-month running mean solar flux at 2800 Mhz ($\bar{S}$) ranges from about 155 to 70. The following is a summary of the principal features noted in these data:

I. Diurnal Variations:

a. Sunrise and sunset, represented by the dashed curves, are the periods of consistent, sharp, daily TEC gradients, with the more rapid rate of change occurring at sunrise.

b. Daytime maximum occurs between 1200 and 1400 hours in winter and the equinoxes and shifts to 1500 to 1700 hours in summer.

c. Nighttime minimum occurs in the pre-dawn hours.

d. Ratio of daytime high to nighttime low is about 4 in summer and 6 in other seasons.

II. Seasonal Variations:

a. Daytime maxima:

1. Two peaks occur yearly at the equinoxes, the

greater being at the vernal equinox near solar maximum and at the autumnal equinox near solar minimum.

2. Winter peak is greater than the summer peak with a ratio of about 1.4 at solar maximum that decreases to nearly 1.0 at solar minimum.

3. Ratio of equinoctial high to solstical low is nearly 2 at solar maximum and decreases to 1.25 at solar minimum.

b. Nighttime minima:

1. Lowest occurs in winter, highest in summer

2. Ratio of summer high to winter low is about 1.4.

III. Solar Cycle Variations:

a. Ratios of observations at solar maximum to those at solar minimum:

1. Daytime maxima:
   Vernal equinox-5:1
   Autumnal equinox-4:1
   Winter-3.5:1
   Summer-3:1

2. Nighttime minima:
   Vernal equinox-5:1
   Autumnal equinox-3.5:1
   Winter-3.5:1
   Summer-4:1

b. An approximately linear relationship exists between TEC and $\overline{S}$ (and $\overline{R_Z}$). This is shown in Figure 2 where the daytime maxima and nighttime minima are plotted for the months of January, March, July, and October which represent the seasonal maxima and minima.

Similar behavior has been reported for observations in the southern hemisphere and in other northern hemisphere locations (Titheridge[5], 1973; Mulkern[6], 1976).

The standard deviation of the observations, in Figure 3, is used to represent the average day-to-day variability of the ionosphere. The isopleths of TEC in units of 10^{15} el/m^2, when compared to those of Figure 1, show that this variability approximates 20-25 percent of the monthly mean in daytime and about 30-35 percent at night. This percentage variability is nearly a constant throughout the solar cycle for all seasons. It therefore indicates that the diurnal, seasonal and solar cycle changes in the average day-to-day variability are proportional to the respective changes in the monthly mean.

Another feature to note is that the daytime variability, when considered in terms of absolute value in TEC, is 2 to 3 times greater than the nighttime variability. This defines daytime as the period when ionospheric effects are most significant.

RADAR CORRECTION

The accuracy of any radar is limited by its capacity to correct for the refraction effect in its range measurement that occurs when a radar pulse passes through the ionosphere. The group velocity of the pulse is less when it passes through the ionosphere than it would be if passing through free space. Therefore, the radar system reports a range measurement with an ionospheric component (ΔR) which is related to the difference between the actual time and the free space time of propagation of the radar pulse:

$$\Delta t = \frac{1}{c}\int_0^s \mu_g \, ds - \frac{1}{c}\int_0^s ds$$

The ionospheric component of the range measurement is:

$$\Delta R = c\Delta t = \int_0^s \mu_g \, ds - \int_0^s ds$$

where μ_g is the group refractive index along the slant path, s, and c is the free space velocity of electromagnetic waves. For VHF and higher frequencies the magnetic field and collision effects can be ignored, and μ_g can be defined in terms of the phase refractive index, μ_p, using the Appleton-Hartree dispersion relation, as follows:

$$\mu_p^2 = 1 - X$$

where:

$$X = Ne^2/\varepsilon_0 m\omega^2 = kN/f^2 = (f_n/f)^2$$

and:

f = radar frequency

f_n = ionospheric plasma frequency

k = 80.5

N = electron density

Then, $\mu_p = \left[1 - (f_n/f)^2\right]^{1/2}$

$$\mu_g = \frac{d}{df}(\mu_p f) = \frac{1}{\mu_p}$$

For $f_n \ll f$:

$$\frac{1}{\mu_p} \approx 1 + X/2$$

To first order the range component due to the ionosphere can then be written

$$\Delta R = 1/2 \int_0^s X\, ds = 40.3/f^2 \int_0^s N(s)\, ds$$

Second order effects are much smaller than the uncertainties of measurement or prediction of TEC and can therefore be ignored (Savich and Vaslyev[7], 1972; Tucker and Fannin[8], 1968).

The integral of the electron density along the slant path to the target is related to TEC by a geometric factor defined as the secant of the zenith angle (χ) at the centroid of the slant integral at a height of 420 km (Titheridge[3], 1972). Then

$$\Delta R = (40.3/f^2)\ (\mathrm{TEC})\ \ (\sec\chi)$$

Therefore the ionospheric component of the range measurement is inversely proportional to the square of the radar frequency and directly proportional to the vertical TEC at the centroid of the slant path.

The significance of the ionospherically induced error in range measurement is apparent in Figure 4, which shows isopleths of the archive TEC data of Figure 1 converted to monthly mean range correction (ΔR), in feet, for a 425 Mhz radar and a target at 1000 km altitude and 5° elevation angle. The daytime maxima in ΔR vary from about 1000 feet in March, 1970 to about 250 feet in March, 1976. The daytime minima vary from more than 500 feet in summer of 1969 and 1970 to less than 200 feet in summer, 1976. Nighttime ΔR is less than 500 feet at all times with minima between 125 feet at solar maximum and 35 feet at solar minimum.

When the median values for range correction are accurately predicted there is still a residual error in range measurement caused by the day-to-day variability shown in Figure 3. When this variability in TEC is converted to variability in range correction (δR_O) the result is the residual error, in feet, shown in Figure 5. The peak daytime δR_O varies from over 150 feet at solar maximum to about 50 feet at solar minimum. The daytime low varies from about 100 feet to 25 feet through this period. The nighttime δR_O is less than 100 feet at all times with a low between 40 feet at solar maximum and 10 feet at solar minimum. Since the day-to-day variability, δR_O, is directly proportional to ΔR, it is the primary source of error in radar range correction.

It has been proposed to reduce the error in range correction, caused by the day-to-day variability of the ionosphere, through use of an adaptive modelling technique. A simulated application of such a technique is presented here for a radar system using the Hamilton, Mass. observations of TEC in conjunction with a prediction of the median range correction.

The computer program (Llewllyn and Bent[9], 1973) used for this study produces a 10-day median of ionospheric parameters for any given time and location. Each of the observations in the archive data was compared with its corresponding prediction and the results are plotted in Figure 6 as isopleths of deviation from the predicted median (δR_m). These isopleths closely correspond to those of the actual variability of the observations, δR_O, in Figure 5. It is then concluded that the model effectively predicts the observed median and can be used as a baseline for evaluating adaptive modeling techniques.

In applying the technique for adaptive modeling, from January, 1968 through December, 1976, each hourly observation at Hamilton, Mass. was used to scale the predicted median for the succeeding 12 hours at 15-minute intervals. The resultant scaled prediction was then compared to its corresponding observation. At the end of each month the root mean square deviation of the observations from each 12-hour scaled prediction was calculated. The general results for the nine years can be summarized as follows:

1. A measurement after sunrise can be used effectively throughout the daytime hours. The resultant r.m.s. error approaches or exceeds δR_m only in the late afternoon near sunset.

2. A measurement after sunset can be used effectively throughout the nighttime hours. The resultant r.m.s. error only exceeds δR_m near sunrise.

3. A simple correction is not possible for long periods spanning the sunrise and sunset transition periods. Therefore the prediction should be made using the unscaled monthly median rather than the adapted median at these times unless measurements can be made as frequently as every 15 to 30 minutes.

This is consistent with results reported for observations of foF2 (Zacharisen[10], 1965).

Residual error for range correction, in feet, using a scaled prediction of the median one hour after updating (δR_{1h}) is shown in the isopleths of Figure 7. When compared with those for δR_m, there is a general reduction of a factor of 2 to 3. The error at the time of the daytime maxima is reduced to less than 75 feet at solar maximum and to about 20 feet at solar minimum. At the time of the daytime minima it varies between 25 feet and 10 feet, and at the time of the nighttime minima from about 20 feet to 5 feet. The lesser degree of improvement near sunrise probably reflects the fact that mechanisms of the pre-sunrise ionosphere differ from those in the post sunrise period, thereby inducing error when projected across the terminator. This is more apparent in the isopleths of *Figure 8 which show* the residual error in range correction using a scaled prediction three hours after updating (δR_{3h}). Within three hours after sunrise, δR_{3h} is equal to or greater than δR_m. At most other times comparison with δR_m shows a reduction in variability with δR_{3h} at the time of the daytime maxima varying between less than 100 feet at solar maximum and about 45 feet at solar minimum. At the time of the daytime minima the variation is from over 50 feet to about 25 feet and at the time of the nighttime minima, from 35 feet to 10 feet.

The comparisons of δR_{1h} and δR_{3h} with δR_m show that the greatest reductions occur at the times the error in range correction due to the variability of the ionosphere is greatest, and therefore most critical: in daytime, at solar maximum. The reduction at these times is nearly a factor of 2 for δR_{3h} and nearly a factor of 3 for δR_{1h}.

EFFECTS OF EXTREME MAGNETIC DISTURBANCE

In some months there are days when TEC has steep gradients that depart several standard deviations from the median. These outliers are associated with periods of severe magnetic disturbance and were selected from the data through the combined criteria of a K_p index of 6 or greater and a departure from the median of ± 180 TEC units. This identified 46 days with behavior that greatly differed from the main body of data in the 9-year period. The presence of these outliers produced extreme values in the monthly statistics for the time periods most affected by the steep gradients. Their exclusion resulted in smoothed statistics that are a more valid representation of the effectiveness of adaptive modelling.

The influence of a single day on the statistics for a month is shown in Figure 9. March 8, 1970 was a day of severe magnetic disturbance, as defined by the K_p indices for the four 3-hour time periods between 1200 and 2400 UT, which were 7+, 8, 9, and 8+, respectively. Between 1400 and 1600 UT, TEC increased by nearly 300 units; between 1600 and 2000 UT there was another overall increase of 200 units, then a decrease of 700 units between 2000 and 2200 UT. The range correction for this day, which is directly proportional to the TEC, is represented by the curve ΔR_d. The difference between ΔR_d and ΔR represents the error in range correction that would have existed if only a prediction of the median had been used in range measurements.

The observations for this day are included in the monthly results represented by the solid curves and have been eliminated in the dashed curves. The results in both cases are comparable for each of the parameters except in the time periods coinciding with the radical behavior of this one day. For those time periods the following effects are observed when this day is excluded:

1. there is little change in ΔR
2. δR_m is noticeably reduced
3. δR_{1h} assumes a relatively smooth behavior with the 50-75 percent reduction expected for a one hour update
4. δR_{30m}, which is the residual error in range correction using a 30 minute update, has no peak afternoon error. The level for the daytime period is consistently lower than the minimum nighttime δR_m.

It is possible to reduce the δR_m even during severely disturbed periods if the time interval for updating is reduced. This can be interpreted from the results for δR_{30m}, where the peak error, for the curve including the disturbed day still represents a *significant reduction* of δR_m.

SUMMARY

Since the error in the range measurement of a radar is directly proportional to the total electron content (TEC) of the ionosphere along the ray path to the target, it can be corrected to first order through use of models that can predict median values of TEC. The average day-to-day variability of TEC is 20-25 percent of its monthly median in day time and 30-35 percent at night. This percentage error is nearly independent of seasonal and solar cycle variations. The absolute error is 2 to 3 times greater in daytime than nighttime.

An adaptive modeling technique combining the use of local measurements with the prediction of median range correction can reduce the residual error significantly, particularly in daytime when the error is greatest. Evaluation of this technique, using nine years of data from Hamilton, Mass. in simulation of actual use by a 425 Mhz radar on a target at 1000 km altitude, 5^{o} elevation angle, has shown that an updated prediction of the median range correction can reduce the residual error by 60 percent even after one hour, and by 30 percent in daytime after three hours. Near sunrise and sunset and during severe magnetic disturbances, which are periods of rapid changes in TEC, the same degree of reduction in error can be maintained by reducing the interval for updating to about 15-30 minutes.

The results of this study are summarized in Table I for the solar maximum conditions, $\overline{S}$ = 155, $\overline{R_z}$ = 110, and the solar minimum conditions, $\overline{S}$ = 71, $\overline{R_z}$ = 10. The values in feet, of the parameters for range correction and its residual errors are listed at the local times of the daily mean maxima and minima for the periods representing the seasonal maxima and minima. The parameters listed are:

ΔR -the ionospheric component of range measurement

δR_m -the residual error in range correction using a median prediction, caused by the day-to-day variability of the ionosphere

δR_{3h} -the residual error in range correction using a scaled median prediction three hours after updating

δR_{1h} -the residual error in range correction using a scaled median prediction one hour after updating

δR_{30m} -the residual error in range correction using a scaled median prediction thirty minutes after updating

TABLE I

	WINTER		VERNAL EQUINOX		SUMMER		AUTUMNAL EQUINOX	
	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN
Solar Maximum ($\overline{R_z}$ = 110; $\overline{S}$ = 155)								
ΔR	750	125	950	175	550	175	900	150
δR_m	135	40	160	55	90	50	160	50
δR_{3h}	90	35	100	35	60	35	90	40
δR_{1h}	50	23	55	23	37	25	37	18
δR_{30m}	35	12	35	12	25	15	30	15
Solar Minimum ($\overline{R_z}$ = 10; $\overline{S}$ = 71)								
ΔR	225	35	225	35	200	45	250	45
δR_m	40	15	55	15	35	10	35	15
δR_{3h}	40	20	45	10	35	10	45	15
δR_{1h}	25	8	25	5	15	8	25	8
δR_{30m}	20	4	15	3	10	5	15	5

To estimate the range correction for other values of $\overline{S}$ it is possible to interpolate or extrapolate to a reasonable approximation by assuming the linear relationship between $\overline{S}$ and TEC, as shown in Figure 2, which can be applied directly to range correction.

These results clearly show that adaptive modelling is successful in reducing the error caused by the day-to-day variability of the ionosphere. Even during periods of severe magnetic disturbances, when errors that far exceed the expected residual error in range measurement are likely to occur, a substantial reduction is possible. The rapid fluctuations that cause these errors cannot be predicted, but their effects can be reduced. The degree of reduction depends on the time interval between measurements for updating, and this allows a system to optimize its mode of operation to meet its range correction requirements.

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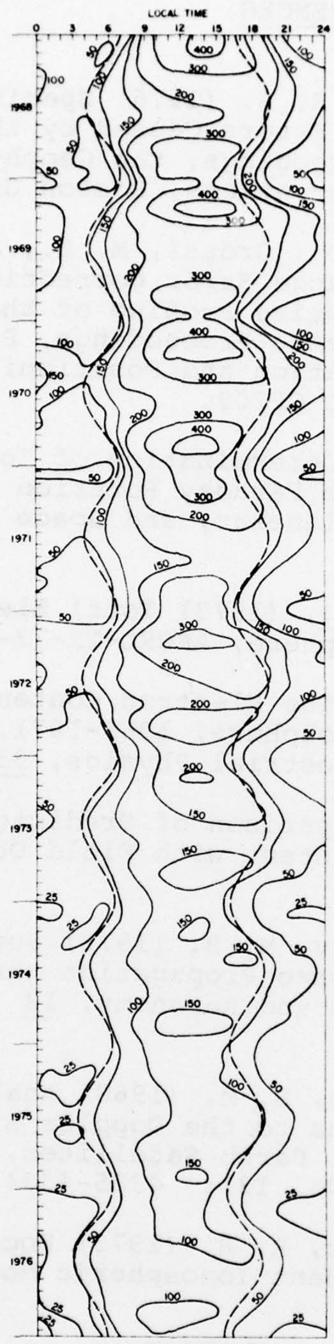


FIGURE 1

MONTHLY MEAN OF THE MEASUREMENTS OF TOTAL ELECTRON CONTENT (TEC X 10^{15} el/M^2) TAKEN AT HAMILTON, MASS. FROM THE FARADAY ROTATION OF THE VHF BEACON ON THE ATS-3 SATELLITE FOR THE PERIOD JANUARY, 1968 THROUGH DECEMBER, 1976

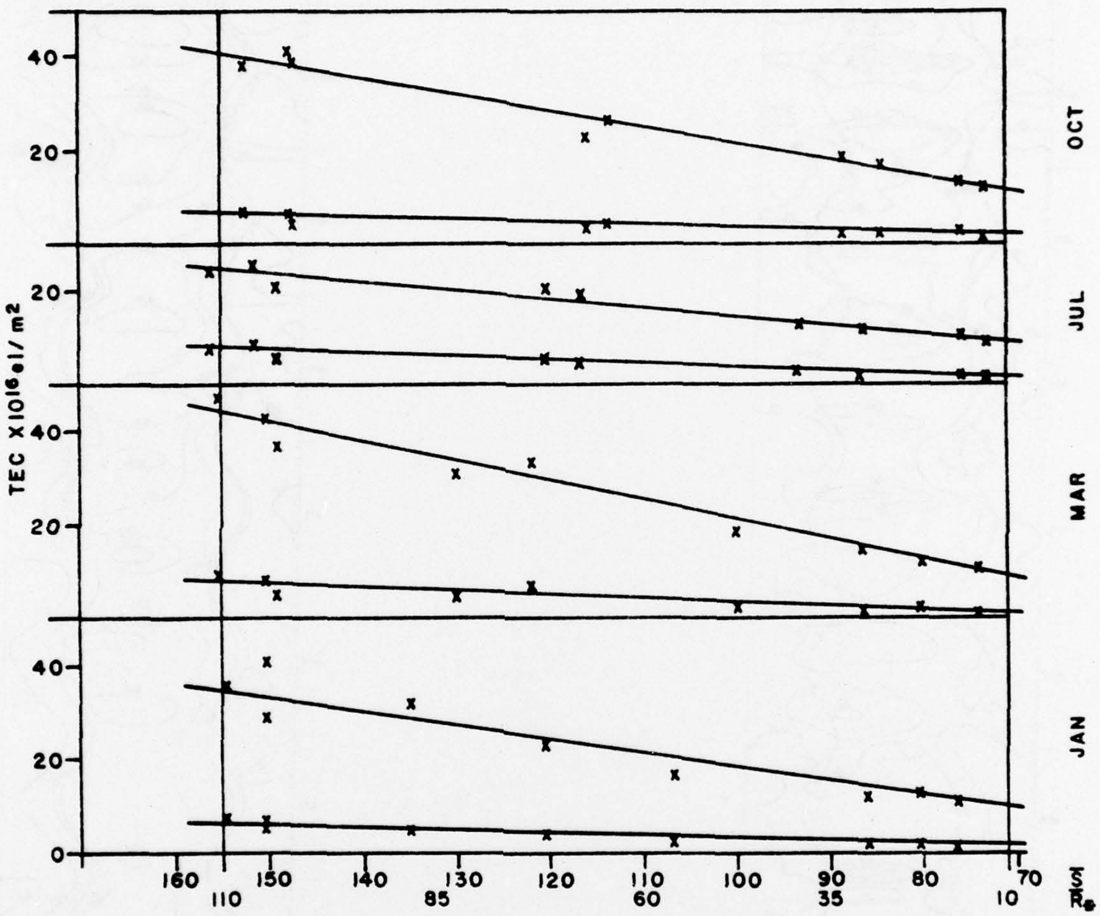


FIGURE 2 THE RELATIONSHIP BETWEEN TOTAL ELECTRON CONTENT (TEC) AND 12-MONTH RUNNING MEAN SOLAR FLUX ($\bar{S}$) FOR THE 9-YEAR PERIOD FROM 1968 THROUGH 1976, SHOWN FOR THE DAYTIME MAXIMA AND NIGHTTIME MINIMA IN MONTHS REPRESENTING EQUINOCTIAL MAXIMA AND SOLSTICIAL MINIMA.

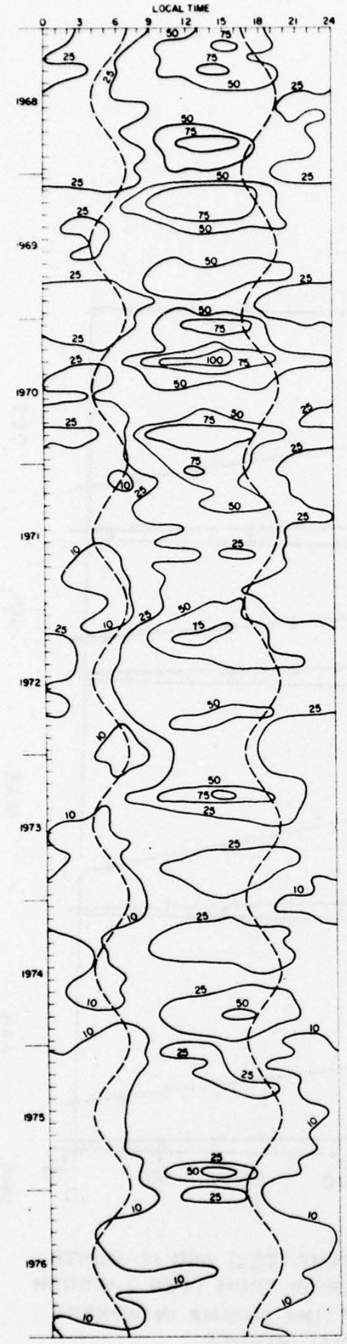


FIGURE 3

STANDARD DEVIATION OF THE MEASUREMENTS OF TOTAL ELECTRON CONTENT (TEC X 10^{15} el/M^2) TAKEN AT HAMILTON, MASS. FOR THE PERIOD JANUARY, 1968 THROUGH DECEMBER, 1976 REPRESENTING THE DAY-TO-DAY VARIABILITY OF THE IONOSPHERE

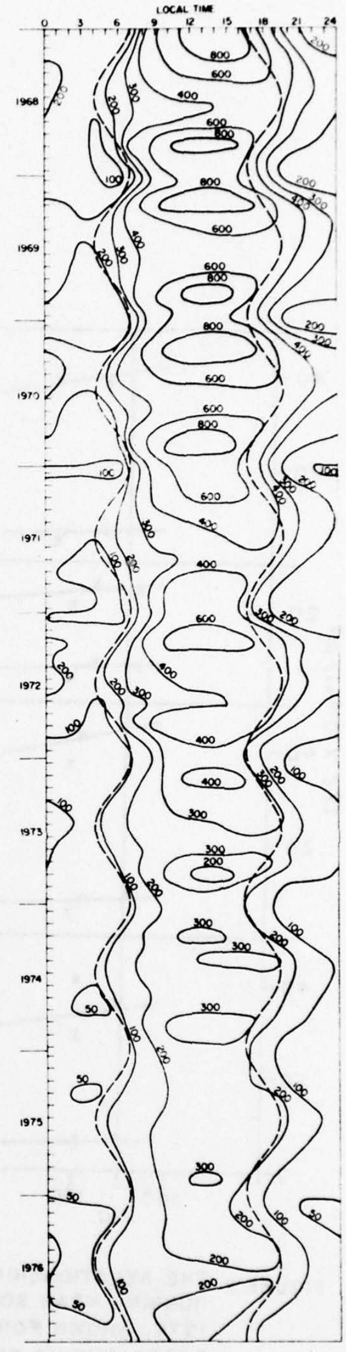


FIGURE 4

MEAN IONOSPHERIC COMPONENT OF RANGE MEASUREMENT (ΔR IN FEET) AT HAMILTON, MASS FOR A 425 MHZ RADAR AND A TARGET AT 1000 KM ALTITUDE, 5^{o} ELEVATION ANGLE

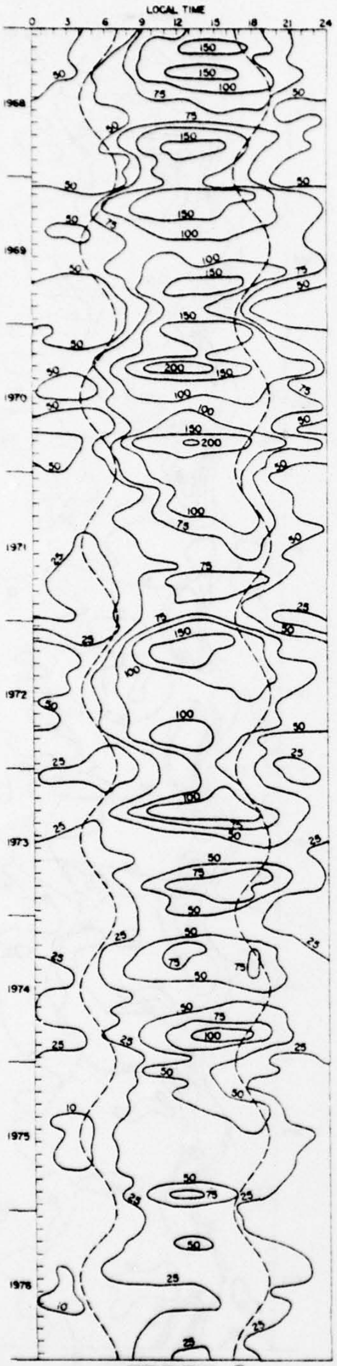


FIGURE 5

RESIDUAL ERROR IN RANGE CORRECTION DUE TO THE DAY-TO-DAY VARIABILITY OF THE IONOSPHERE (δRo IN FEET) AT HAMILTON, MASS. FOR A 425 MHZ RADAR AND A TARGET AT 1000 KM ALTITUDE, 5° ELEVATION ANGLE

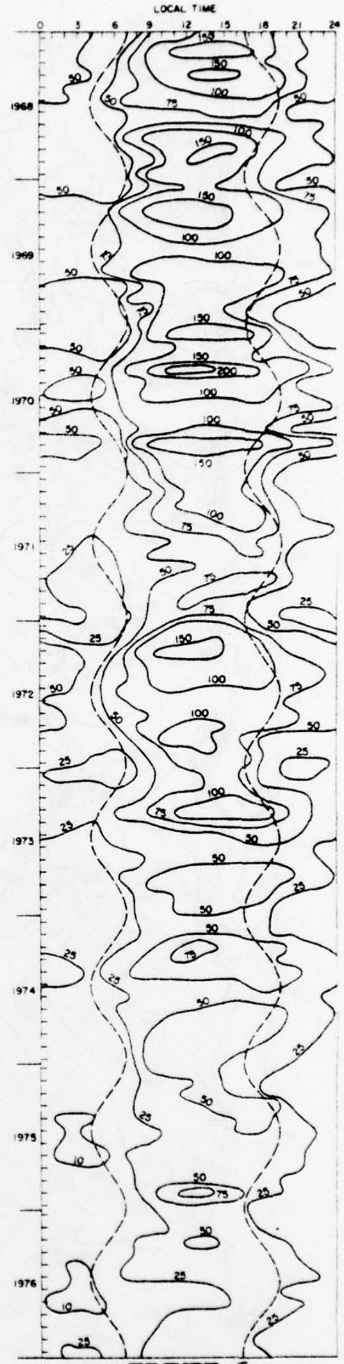


FIGURE 6

RESIDUAL ERROR IN RANGE CORRECTION DUE TO THE DAY-TO-DAY VARIABILITY OF THE IONOSPHERE USING A PREDICTION OF THE MEDIAN IONOSPHERIC COMPONENT OF RANGE MEASUREMENT (δRm IN FEET) AT HAMILTON, MASS. FOR A 425 MHZ RADAR AND A TARGET AT 1000 KM ALTITUDE, 5° ELEVATION ANGLE

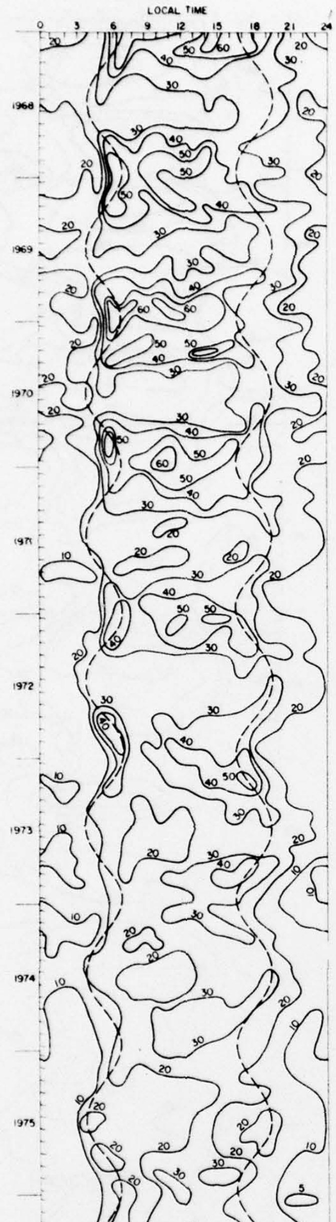


FIGURE 7

RESIDUAL ERROR IN RANGE CORRECTION USING A SCALED MEDIAN PREDICTION ONE HOUR AFTER UPDATING (δR_{1h} IN FEET) AT HAMILTON, MASS. FOR A 425 MHZ RADAR AND A TARGET AT 1000 KM ALTITUDE, 5^{o} ELEVATION ANGLE

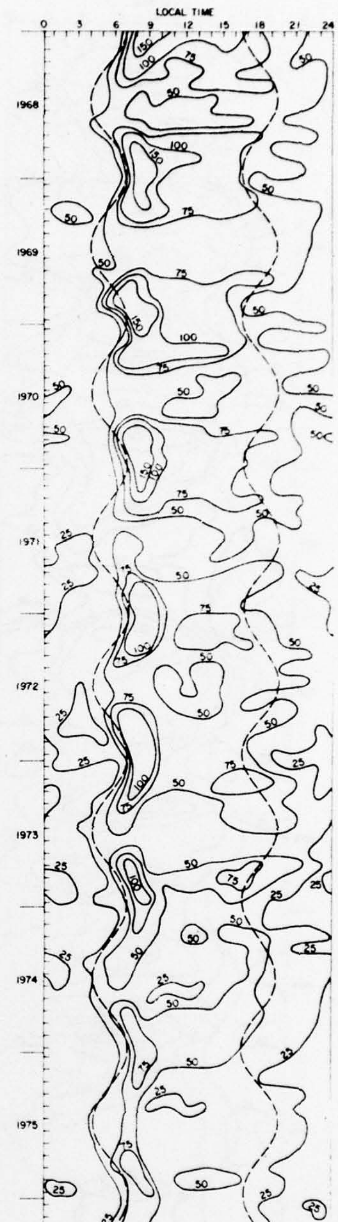
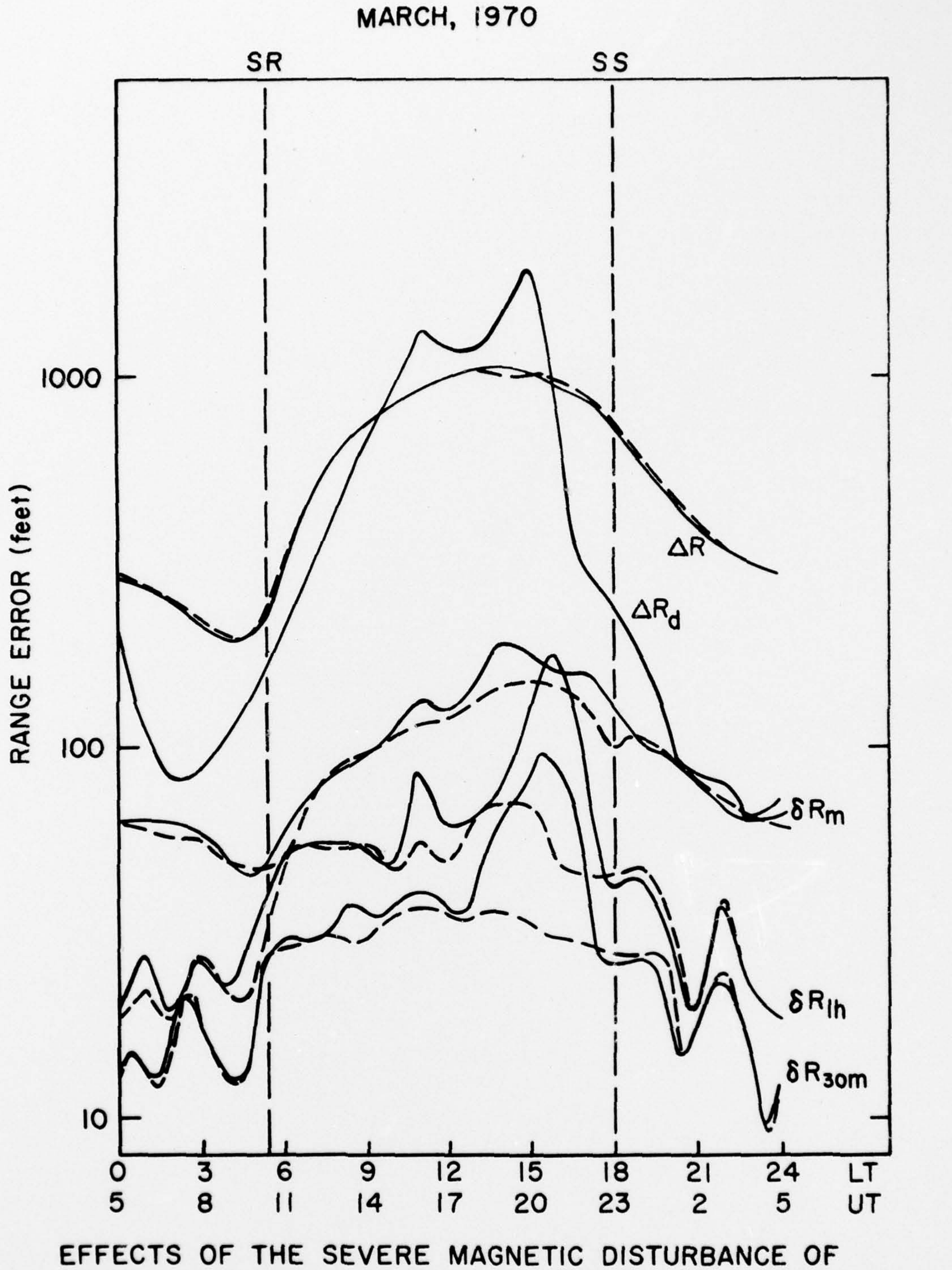


FIGURE 8

RESIDUAL ERROR IN RANGE CORRECTION USING A SCALED MEDIAN PREDICTION THREE HOURS AFTER UPDATING (δR_{3h} IN FEET) AT HAMILTON, MASS. FOR A 425 MHZ RADAR AND A TARGET AT 1000 KM ALTITUDE, 5^{o} ELEVATION ANGLE



EFFECTS OF THE SEVERE MAGNETIC DISTURBANCE OF MARCH 8, 1970 ON RANGE CORRECTION AND THE STATISTICS FOR EVALUATING THE ADAPTIVE MODELING TECHNIQUE AT HAMILTON, MASS. FOR A 425 MHZ RADAR AND A TARGET AT 1000 KM ALTITUDE, 5° ELEVATION ANGLE

FIGURE 9